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MODULAR REGENERATIVE HEAT EXCHANGER SYSTEM

CLAIM OF PRIORITY

This application claims priority from U.S. Provisional Application No. 60/352,097 filed January 23, 2002.

FIELD AND BACKGROUND OF THE INVENTION

The present invention is directed to an apparatus and method for transferring heat from a hot fluid to a cold fluid using regenerative heat-transfer techniques.

Regenerative heat-exchangers have long been used as a means for transferring heat from a hot fluid to a cold fluid. The theory and operation of regenerative heat-exchangers is well-known and documented in the prior art.

For example, US Patent 3,225,819 to Stevens discloses a regenerative heat exchanger having separate regenerative heat exchanger chambers. An electro-mechanical control system controls the flow of the hot and cold gases through each of the chambers to provide continuous flow of the hot and cold gases through the system. However, such a regenerative heat exchanger is expensive to fabricate, takes excessive plant space, and is not very flexible with respect to operation under widely varying operating condition. Therefore, it has been supplanted by rotary regenerative heat exchangers (more commonly called "Ljungstrom wheels") which are widely used in power plant applications to increase the thermal efficiency of boilers. These rotary regenerative heat exchangers are commercially available from manufacturers such as Air Preheater Co. (USA), Howden Co. (UK) and others.

However, these rotary regenerative heat exchangers suffer from a number of disadvantages. For example, they rely on sliding seals to separate the hot gas from the cold gas. As well documented in the prior art, such as in US patent 6,227,150 to Finnemore, the sliding seals get rapidly worn out and result in excessive cross-leakage between the hot gas and the cold gas. The seals therefore require frequent replacement resulting in excessive boiler down-time and excessive maintenance costs. The cross-leakage results also in excessive parasitic power consumption and reduced boiler fuel-conversion efficiency. Alternately, special seal adjusting devices have to be used to minimize the cross-leakage during operation. This greatly adds to the cost and complexity of the rotary regenerative heat exchanger.

Furthermore, for economy of manufacturing, rotary regenerative heat exchangers are normally manufactured to handle large quantities of gas. The large size causes severe thermal deformation problems during the operation of the rotary regenerative heat exchanger. Since only two or three rotary regenerative heat exchangers are generally used in a typical power-plant, a minor breakdown of a component in the rotary regenerative heat exchanger requires that the boiler be shut down or run at a 50% capacity while repairs are made to the rotary regenerative heat exchanger. This causes large losses in production of electrical energy and loss of revenue to the power plant.

Further, the large size of the rotary regenerative heat exchanger generally requires a great deal of on-site field fabrication and installation, which results in high installation costs.

Yet further, during off-peak hours, when the megawatt-load demand on the boiler is low, the amount of gas flowing through the rotary regenerative heat exchanger is greatly reduced. The reduced flow results in reduced gas velocity through the rotary regenerative heat exchanger. This, in turn, results in increased deposition of fly-ash on the surface of the heat-sink material of the rotary regenerative heat exchanger. The overall result is a loss of heat-transfer efficiency and a need for more frequent cleaning of the rotary regenerative heat exchanger. The additional cleaning using soot-blowers and/or other means generally increases the parasitic steam consumption of the regenerative heat exchanger while reducing the overall fuel-conversion efficiency of the boiler.

Therefore, it will be apparent that a need exists for a regenerative heat exchanger that provides a low cross-leakage and a capability for handling variable quantities of gases. The regenerative heat exchanger should also provide generally optimum operation throughout the full turndown range of flow of the gases. Further, the regenerative heat exchanger should not require sliding seals to separate the cold and hot gases thereby reducing process down-time, maintenance costs, parasitic power and steam consumption. Yet further, the regenerative heat exchanger should use relatively inexpensive, non-thermally-deformable, corrosion-resisting heat-sink material. Such a regenerative heat exchanger should be economical to manufacture, transport, and install at the job-site. A process using a regenerative heat exchanger with the above advantages will operate at a higher efficiency with reduced capital and operating costs.

SUMMARY OF THE INVENTION

In one aspect of the invention, hot and cold gas is alternately passed through a plurality of independently operable stationary regenerative heat exchanger modules to simulate the operation of a rotary regenerative heat exchanger having revolving heat transfer sectors. In the regenerative heat exchanger module, the heat-sink media gets heated by absorbing the heat from the hot gas, thereby cooling the hot gas. After a period of time, the flow of hot gas to the regenerative heat exchanger module is shut off and cold gas is introduced into the regenerative heat exchanger module. The cold gas gets heated by absorbing heat from the previously heated heat-sink material, thereby cooling the heat-sink media. After a second period of time, the flow of cold gas to the regenerative heat exchanger module is shutoff and the hot gas is again re-introduced into the regenerative heat exchanger module. The above cycle is repeated as long as required. The periods for the flow of hot and cold gas through each of the regenerative heat exchanger module are staggered so that the hot and cold gases progressively flow through each of the stationary regenerative heat exchanger modules, thereby simulating the operation of a rotary regenerative heat exchanger having revolving heat transfer sectors.

The dimensions of the regenerative heat exchanger modules are selected to facilitate factory assembly, testing, and shipment of the module by road or rail and for easy installation of the module at the job-site. Inlet and outlet dampers on the hot and cold gas sides of the regenerative heat exchanger module control the flow of the hot and cold gases. The damper blades are moved by pneumatic, hydraulic or electric actuators.

The heat sink media in the regenerative heat exchanger module can be metallic or refractory plates, which can further be configured as multi-layered monolith blocks. The flow of the hot and cold gas through each regenerative heat exchanger module can be in the same or in opposite directions to each other. Each of the regenerative heat exchanger modules can process either an equal fraction or an unequal fraction of the total flow quantity of hot or cold gas through the regenerative heat exchanger system. Yet further, the number of regenerative heat exchanger modules receiving the hot gas can either be equal or not equal to the number of regenerative heat exchanger modules that receive the cold gas.

Each of the regenerative heat exchanger modules can have an idle mode of operation wherein the flow of the hot and cold gases to the regenerative heat exchanger module is temporarily shut off while the regenerative heat exchanger module is in transition between the hot and cold gases. Yet further, each of the regenerative heat exchanger modules can be taken off-line for repairs or maintenance by manual selection through the regenerative heat exchanger system controller. Alternately, the regenerative heat exchanger module can be automatically taken off-line by the regenerative heat exchanger system controller whenever the flowrate of the gases drops as a result of reduced demand on the boiler. While the regenerative heat exchanger module is off-line, the remaining regenerative heat exchanger modules continue to operate to simulate a rotary regenerative heat exchanger.

Another aspect of the invention includes a regenerative heat exchanger system controller. The regenerative heat exchanger system controller can be an electronic programmable computer, which executes computer code for operating each regenerative heat exchanger module and for staggering the operation of each regenerative heat exchanger module to simulate the operation of a rotary regenerative heat exchanger. The regenerative heat exchanger system controller can include an idle mode of operation and means for manually or automatically selecting a regenerative heat exchanger module for off-line operation as described above.

Yet another aspect of the invention includes a method of operating a number of independently operable regenerative heat exchanger modules to simulate the operation of a rotary regenerative heat exchanger. The method includes passing a first gas through a regenerative heat exchanger module for a first period of time and then optionally idling it for a brief period of time and then passing a second gas through the regenerative heat exchanger module for a second period of time. The operation of each of the regenerative heat exchanger modules is staggered to simulate the operation of a rotary regenerative heat exchanger. Upon the shutdown of a regenerative heat exchanger module, the remaining regenerative heat exchanger modules are continued to operate to simulate the operation of a rotary regenerative heat exchanger. Further, the period of operation with the first and second gases can be kept the same or can be changed when the remaining regenerative heat exchanger modules are operated.

These and other features, aspects, and advantages of the present invention will become better understood with reference to the following drawings, description, and claims.

BRIEF DESCRIPTION OF THE DRAWINGS:

Figures 1A, 1B, and 1C are isometric representations, which show the details of different embodiments of a regenerative heat exchanger module according to the present invention.

Figure 2 is an isometric representation of a regenerative heat exchanger system, which is assembled from a plurality of the regenerative heat exchanger modules shown in Figure 1A.

Figure 3 is a schematic representation of an electrical control diagram, which shows the control systems for the regenerative heat exchanger system of Figure 2 and the regenerative heat exchanger modules of Figure 1A.

Figure 4 is a flow-chart which shows the control logic for the control system for the regenerative heat exchanger system of Figure 2.

Figure 5 is a flow-chart which shows the control logic for the control system for the regenerative heat exchanger module of Figure 1A.

Figure 6 shows Tables 3,4,5,6,7, and 8 which represent the different operating modes of the regenerative heat exchanger modules in a regenerative heat exchanger system.

DETAILED DESCRIPTION:

Referring now to Figures 1A, and 2, Figure 1A shows a partially cut-away isometric representation of a single regenerative heat exchanger module according to the present invention and Figure 2 shows a plurality of regenerative heat exchanger modules of Figure 1A assembled into regenerative heat exchanger system 100.

As shown in Figure 2, regenerative heat exchanger system 100 is comprised of a number of regenerative heat exchanger modules. Figure 2, shows as an example, five regenerative heat exchanger modules, which are represented by the reference numerals 1, 2, 3, 4, and 5. The five regenerative heat exchanger modules could be identical to each other or they could have some variations depending on design requirements.

Figure 1A shows details of a typical regenerative heat exchanger module, in this case regenerative heat exchanger module 1. Regenerative heat exchanger module 1 is shown configured as an H-shaped housing 1h having a middle section 1.1 and ducts 1.3, 1.4, 1.5, and 1.6. Housing 1h can be fabricated of carbon-steel or stainless steel or other suitable material and can be internally or externally insulated to reduce heat losses. As seen in the cutaway representation of regenerative heat exchanger module 1 of Figure 1A, the middle section 1.1 is configured as a box with an open top and bottom and a right side 1.1r, a left side 1.1l, a front side 1.1f, and a back side 1.1b.

A heat sink media 1.2 is contained within the middle section 1.1. Heat sink media 1.2 is supported on heat sink media support 1.7, which is located near the lower end of middle section 1.1. Heat sink media 1.2 can be any standard heat sink media, which is suitable for use in conventional regenerative heat exchangers. For example, it could be structured metallic plates as described in US patent 5,318,102 to Spokoyny et al. Alternatively, it could be made of a refractory material such as ceramic stoneware or porcelain. As an example, it could be ceramic structured media blocks such as those available from Lantec Products Inc, USA under the trade-name of Multi-Layered Monolith Media (MLM®) and described in US patent 5,852,636 to Lang et al. Alternatively, it could be random packing such as ceramic saddles, also available from Lantec Products Inc, USA or metal rods or balls or other shapes that could be poured to form a packed heat-storage bed. All these forms of heat-sink material are well known in the art.

The upper free volume in middle section 1.1 above heat sink media 1.2 is shown by the reference numeral 1.1x in Figure 1A.

Heat sink media support 1.7 is any means of supporting heat sink media 1.2 such as grates or perforated plates which are capable of supporting the weight of heat sink media 1.2 while allowing the hot or cold gas to flow into heat sink media 1.2. Such means of support are well described in the prior art such as US Patent 5,770,165 to Truppi et al.

The lower free volume in middle section 1.1 under the heat sink media support 1.7 is shown by the reference numeral 1.1y in Figure 1A.

The vertical arms and legs of housing 1h are configured as ducts 1.3, 1.4, 1.5, and 1.6 respectively for the flow of the hot and cold gases into and out of housing 1h. While the ducts are shown as square or rectangular cross-sectioned in Figures 1A, 1B, 1C, and 2, they could also be circular or any other shape in cross-section. Duct 1.3 has an open end 1.3.1, which allows for the flow of hot gas H into housing 1h. Similarly, duct 1.6 has an open end 1.6.1, which allows for the flow of the cooled hot gas shown as H' out of housing 1h.

A flow control means is located in duct 1.3 to control the flow of the hot gas H into housing 1h. In Figure 1A, flow control means is shown as a butterfly damper 1.3.2. However, the flow control means could also be any other valve device such as a poppet valve (as shown in Figure 1B), a guillotine damper, a two-way diverter damper (as shown in Figure 1C), or any other device which controls the flow of a gas. Such flow control devices are well-known in the art and are available from US manufacturers such as Precision Engineered Products Inc., Mosser Dampers Inc., Bachmann Dampers Inc. and others.

Similarly, a butterfly damper 1.6.2 is shown located in duct 1.6 for controlling the flow of cooled hot gas H' out of housing 1h.

During operation of regenerative heat exchanger module 1, hot gas H enters inlet 1.3.1 into duct 1.3 and flows past open damper 1.3.2 into upper volume 1.1x of middle section 1.1. The hot gas H then flows downwards through heat sink media 1.2. Since heat sink media 1.2 is relatively cooler than hot gas H as a result of a previous flow of cold gas C through it (as will be described below), hot gas H gives up its heat to heat transfer media 1.2. Therefore heat sink media 1.2 is heated while hot gas H is cooled to cooled hot gas H'. Cooled hot gas H' then flows downwards through media support 1.7 into lower volume 1.1y of middle section 1.1. The cooled hot gas H' then flows into duct 1.6 and flows past open damper 1.6.2 to outlet 1.6.1 from where it exits housing 1h.

Similarly, duct 1.5 of housing 1h has an open end 1.5.1, which allows for the flow of cold gas C into housing 1h. Also, duct 1.4 has an open end 1.4.1, which allows for the flow of heated cold gas shown as C' out of housing

1h. Damper 1.5.2 is located in duct 1.5 to control the flow of cold gas C into housing 1h. Similarly, damper 1.4.2 is located in duct 1.4 for controlling the flow of heated cold gas C' out of housing 1h. During operation of regenerative heat exchanger module 1, the cold gas C enters inlet 1.5.1 into duct 1.5 and flows past open damper 1.5.2 into lower section 1.1y of middle section 1.1. Cold gas C then flows upwards through heat sink media support 1.7 into heat sink media 1.2.

Since, as described above, heat sink media 1.2 has been previously heated by the flow of hot gas H, heat sink media 1.2 is at a relatively higher temperature than cold gas C. Heat sink media 1.2 therefore gives up its heat to cold gas C which in turn is heated to heated cold gas C'. Heated cold gas C' then flows out of the cooled heat sink media 1.2 into upper volume 1.1x of middle section 1.1. The heated cold gas then flows into duct 1.4 and flows past open damper 1.4.2 to outlet 1.4.1 from where it exits housing 1h.

Dampers 1.3.2, 1.4.2, 1.5.2, and 1.6.2 can all be of the same type such as butterfly dampers or they can be of different types such as two-way diverter dampers (as shown in Figure 1C) or poppet dampers (as shown in Figure 1B) without departing from the spirit of the invention. Further, as shown in Figure 3, individual actuators 1.3a, 1.4a, 1.5a, 1.6a can operate each of dampers 1.3.2, 1.4.2, 1.5.2, and 1.6.2. Alternately, one or more common actuators can be used in any combination to operate dampers 1.3.2, 1.4.2, 1.5.2, and 1.6.2. As is well known, actuators 1.3a, 1.4a, 1.5a, 1.6a can be operated by electrical energy or by a pressurized fluid such as compressed air or hydraulic fluid. The use of actuators to operate dampers in the regenerative heat exchanger modules is well known in the art. For example, pneumatically or hydraulically actuators (commercially available from Parker-Hannifin Inc., USA or other manufacturers) or electrically operated actuators (commercially available from Foxboro-Jordan Inc, USA or other manufacturers) could be used to move the dampers. As will be described below, these actuators can be controlled according to a pre-programmed sequence of operation by electrical control logic such as relays or by computer control means such as micro-controllers or Programmable Logic Controllers.

As is well known in the regenerative heat-exchanger art, dampers 1.3.2, 1.6.2, 1.5.2, and 1.4.2 are operated so that only the hot gas or the cold gas can flow through housing 1h at any given time. Dampers 1.3.2, 1.6.2, 1.5.2, and 1.4.2 of regenerative heat exchanger module 1 are controlled by a regenerative heat exchanger module controller 1p, which is described in detail in the descriptions of Figures 3 and 5. Initially, regenerative heat exchanger module controller 1p opens dampers 1.3.2 and 1.6.2 and closes dampers 1.5.2 and 1.4.2 to enable hot gas H only to flow through the previously cooled heat sink media 1.2. After a first period of time, after heat sink media 1.2 has been heated to a required level or hot gas H has been cooled to a required maximum level, regenerative heat exchanger module controller 1p closes dampers 1.3.2 and 1.6.2 to shut off the flow of hot gas H into housing 1h. Regenerative heat exchanger module controller 1p then opens dampers 1.5.2 and 1.4.2 to allow the flow of cold gas C into housing 1h. After a second period of time, after heat sink media 1.2 has been cooled to a required level or cold gas C has been heated to a required level, regenerative heat exchanger module controller 1p closes dampers 1.5.2 and 1.4.2 to shut off the flow of cold gas C into housing 1h. The second period of time may or may not be equal to the first period of time. Regenerative heat exchanger module controller 1p then opens dampers 1.3.2 and 1.6.2 to allow the flow of hot gas H into housing 1h to heat again the cooled heat sink media 1.2. Regenerative heat exchanger module controller 1p repeats this cycle of heating and cooling heat sink media 1.2 by alternately flowing hot gas H and cold gas C through it as long as required for the operation of regenerative heat exchanger module 1.

As shown in Figure 3, regenerative heat exchanger module controller 2p, 3p, 4p, and 5p are provided for each of the other regenerative heat exchanger modules 2, 3, 4, and 5 respectively. Regenerative heat exchanger module controller 2p, 3p, 4p, and 5p control the operation of each of the actuators of regenerative heat exchanger modules 2, 3, 4, and 5 respectively. Thereby, a sequence of actuator operations, similar to that described above for regenerative heat exchanger module 1, can also be performed for each regenerative heat exchanger modules 2, 3, 4, and 5 in Figure 2. Thus each of regenerative heat exchanger modules 1, 2, 3, 4, and 5 is capable of operating as individual regenerative heat exchangers for transferring heat from a hot gas H to a cold gas C. As will be described below with reference to Figure 2, the individually operable regenerative heat exchanger modules 1, 2, 3, 4, and 5 are combined into regenerative heat exchanger system 100 for simulating the operation of a rotary regenerative heat exchanger.

While the physical configuration of regenerative heat exchanger module 1 has been shown to be H-shaped as described above, other configurations can also be used without departing from the spirit of the invention.

As shown in Figure 2, regenerative heat exchanger modules 2, 3, 4, and 5 are constructed and operated similar to regenerative heat exchanger module 1. Thus regenerative heat exchanger module 2 has heat sink media 2.2, hot gas inlet damper 2.3.2, cooled hot gas outlet damper 2.6.2, cold gas inlet damper 2.5.2, and heated cold gas outlet damper 2.4.2; regenerative heat exchanger module 3 has heat sink media 3.2, hot gas inlet damper 3.3.2, cooled hot gas outlet damper 3.6.2, cold gas inlet damper 3.5.2, and heated cold gas outlet damper 3.4.2; regenerative heat exchanger module 4 has heat sink media 4.2, hot gas inlet damper 4.3.2, cooled hot gas outlet damper 4.6.2, cold gas inlet damper 4.5.2, and heated cold gas outlet damper 4.4.2; and regenerative heat exchanger module 5 has heat sink media 5.2, hot gas inlet damper 5.3.2, cooled hot gas outlet damper 5.6.2, cold gas inlet damper 5.5.2, and heated cold gas outlet damper 5.4.2.

It is not necessary that regenerative heat exchanger modules 2, 3, 4, and 5 be identical to regenerative heat exchanger module 1 as long they possess the major features described above for regenerative heat exchanger module 1. As shown in Figure 2, common duct manifolds 8c, 8c', 8h, and 8h' are provided to individually route the cold gas C, the heated cold gas C', the hot gas H', and the cooled hot gas H' to and from the regenerative heat exchanger system 100. Each of the duct manifolds have individual openings that are connected to each of the openings (for example, openings 1.3.1, 1.4.1, 1.5.1, and 1.6.1 of regenerative heat exchanger module 1) in each of the regenerative heat exchanger modules 1, 2, 3, 4, and 5 of regenerative heat exchanger system 100.

In Figure 2, five regenerative heat exchanger modules have been shown to create regenerative heat exchanger system 100. However, it will be obvious that any number of regenerative heat exchanger modules could be used to create regenerative heat exchanger system 100. The number of regenerative heat exchanger modules will depend on the individual flow capacity of each of the regenerative heat exchanger modules and the total flow requirements of regenerative heat exchanger system 100. Thus in the case of the regenerative heat exchanger system 100 shown in Figure 2, each of the regenerative heat exchanger modules would process one-half of the total flow of the hot gas or the cold gas respectively. As another example, each module in a regenerative heat exchanger system containing "N" modules would treat "2/N" of the total flow of the hot or cold gases that are flowed through the system if "N" is an even integer. Alternatively, each module would treat "2/(N-1)" of the total flow of the hot and cold gases that are flowed through the regenerative heat exchanger system if "N" is an odd integer assuming one regenerative heat exchanger module is idled. However, it is not necessary that each of the regenerative heat exchanger modules be sized to treat equal amounts of the hot or cold gas. They could even be sized to treat different fractions of the total quantity of hot or cold gas to be processed by the regenerative heat exchanger system. For example, to accommodate plant space or other requirements, four modules could be designed to process 10%, 20%, 30%, and 40% of the total flow of the hot gas respectively.

It is also not necessary that the regenerative heat exchanger modules be identical to each other as shown in Figure 2. For example, the positions of hot gas and cold gas inlet and outlet ducts can be changed to accommodate plant duct layout requirements without departing from the spirit of the invention.

Further, shipping dimension constraints would also determine the size and number of regenerative heat exchanger modules required to create a regenerative heat exchanger system for any given application. As a practical consideration, the dimensions of the regenerative heat exchanger modules would be less than 180 inches wide by 168 inches high for shipping by road or rail. This geometry is very advantageous for manufacture of the regenerative heat exchanger modules in a fabrication shop. In such a situation, the regenerative heat exchanger modules could be completely assembled with dampers, actuators, controls, and heat-sink media in the fabrication shop. The completely assembled regenerative heat exchanger modules can then be easily shipped by road or rail to the power-plant or other installation site. Each of the completely assembled regenerative heat exchanger modules can then be easily dropped into place in the desired location at the installation site to provide the complete regenerative heat exchanger system shown in Figure 2.

For economy, ease of manufacturing, and assembly, it is advantageous that the regenerative heat exchanger modules be identical. This would greatly speed up the manufacture of the regenerative heat exchanger modules and facilitate the assembly of the regenerative heat exchanger modules into the regenerative heat exchanger system as described above. This is a great advantage over current state of the art rotary regenerative heat exchangers, which are too large to ship in one piece and therefore require large amounts of fieldwork and downtime for installation. The use of the regenerative heat exchanger modules as described in the claimed invention will greatly reduce the overall cost and time required for installation of a regenerative heat exchanger.

Yet another advantage of the use of regenerative heat exchanger modules lies in the use of pressure-sealed dampers to control flow. As described in the previously referenced US patent to Finnemore, rotary regenerative heat exchangers have a severe sealing problem which permits the cross-leakage of the hot gas into the cold gas or vice versa. For example, it is known that the typical sliding seal in the rotary heat exchanger used in a power-plant boiler will leak almost 20 to 25 percent of the combustion air into the flue gas stream after the seal has been in operation for a relatively short period of time. At this point, the thermal efficiency of the rotary regenerative heat exchanger drops sharply and operation of the rotary regenerative heat exchanger becomes uneconomical necessitating the replacement of the seal. Further, the leakage causes a parasitic power usage of up to 10% of the electrical power produced by the power-plant for the sole purpose of raising the leaked, unused combustion air to the required static pressure required for the operation of the boiler. Replacement of the seal requires that the power-plant be shut down and results in lost production and uneconomical operation of the power-plant.

In comparison to the above situation, the dampers used in the regenerative heat exchanger modules of the present invention have almost negligible (expected to be less than 0.5 percent) leakage between the hot and cold gases during its operating lifetime. Further, these dampers do not have any sliding seals, which require frequent replacement. Thus down-time is reduced resulting in more economical operation and increased utilization of the power-plant.

Yet another advantage of using the regenerative heat exchanger modules described above is that the heat sink material is stationary. Therefore, the complex mechanical drive system, which is used to rotate the wheel containing the heat-sink material in the rotary regenerative heat exchanger, is not required.

Regenerative heat exchanger system 100 can be operated to simulate the operation of a rotary regenerative heat exchanger as shown in Table-1 which shows the sequence of operation of regenerative heat exchanger modules 1, 2, 3, 4, and 5. In Table-1, H = Heating bed wherein the hot gas dampers are open to admit hot gas into the heat sink media bed to "heat" the bed while the cold gas dampers are closed to prevent the flow of cold gas into the bed; C = Cooling bed wherein the cold gas dampers are open to admit cold gas into the heat sink media bed to "cool" the bed while the hot gas dampers are closed to prevent the flow of hot gas into the bed; I = Idle bed where all dampers are closed to prevent the flow of either the hot gas or the cold gas into the heat sink media bed; and T = Transition bed where the hot gas damper is moving from an open or closed position to a closed or open position or where the cold gas damper is moving from an open or closed position to a closed or open position.

In Table-1, the column for each module represents the operation of the controller for that regenerative heat exchanger module while the entire table represents the operation of the controller 100p for the regenerative heat exchanger system 100. The control logic for each individual regenerative heat exchanger module is shown using the control logic for regenerative heat exchanger module 1 as an example in Figure 5. The control logic for regenerative heat exchanger system 100 is shown in Figure 4. It will be obvious that any odd number, greater than or equal to three, of regenerative heat exchanger modules can be utilized using the same control philosophy even though Table-1 shows a regenerative heat exchanger system containing 5 regenerative heat exchanger modules.

TABLE-1

Regenerative heat exchanger Module No:	1	2	3	4	5

Module Controller No:	1p	2p	3p	4p	5p
Module Operating Mode:	H	H	I	C	C
	T	H	T	C	C
	I	H	H	C	C
	T	H	H	T	C
	C	H	H	I	C
	C	T	H	T	C
	C	I	H	H	C
	C	T	H	H	T
	C	C	H	H	I
	C	C	T	H	T
	C	C	I	H	H
	T	C	T	H	H
	I	C	C	H	H
	T	C	C	T	H
	H	C	C	I	H
	H	T	C	T	H
	H	I	C	C	H
	H	T	C	C	T
	H	H	C	C	I
	H	H	T	C	T

H	H	I	C	C	(Original condition at start of table)

Referring to Table-1, regenerative heat exchanger system controller 100p instructs regenerative heat exchanger module controllers 1p and 2p to open dampers 1.3.2, 1.6.2, 2.3.2, and 2.6.2 and close dampers 1.4.2, 1.5.2, 2.4.2, and 2.5.2 in regenerative heat exchanger modules 1 and 2 respectively. Thus, regenerative heat exchanger modules 1 and 2 are initially in a "heating" mode wherein the hot gas H is flowed through heat sink media 1.2 and 2.2.

Similarly, regenerative heat exchanger system controller 100p instructs regenerative heat exchanger module controllers 4p and 5p to open dampers 4.4.2, 4.5.2, 5.4.2, and 5.5.2 and close dampers 4.3.2, 4.6.2, 5.3.2, and 5.6.2 in regenerative heat exchanger modules 4 and 5 respectively. Thus regenerative heat exchanger modules 4 and 5 are in a "cooling" mode wherein the cold gas C is flowed through heat sink media 4.2 and 5.2. In the control system shown in Table-1, the heating mode period is equal to the cooling mode period. However, other control schemes with unequal heating mode and cooling mode periods can also be used.

Initially, in Table-1, regenerative heat exchanger system controller 100p instructs regenerative heat exchanger module controller 3p to close all four dampers. Thus regenerative heat exchanger module 3 is an "idle" mode wherein neither the hot gas H nor the cold gas C is flowed through it. The idle mode time is equal to P/M where P = heating mode period = cooling mode period (including damper transition times) and M = number of regenerative heat exchanger modules receiving the hot gas when the subject regenerative heat exchanger module is idle. Thus, in Table-1, if P equals 20 seconds, then M would equal 2 and the idle mode time would equal 10 seconds.

Controller 100p for operation of regenerative heat exchanger system 100 as represented by Table-1 is designed so the flow of hot gas H can be enabled in regenerative heat exchanger module 1 before it is enabled in regenerative heat exchanger module 2. Therefore, in Table-1, regenerative heat exchanger module 1 is more advanced in the heating mode than regenerative heat exchanger module 2. Similarly, the controller for operation of the regenerative heat exchanger system represented by Table-1 is designed so that the flow of cold gas C was enabled in regenerative heat exchanger module 4 before it was enabled in regenerative heat exchanger module 5. Therefore, in Table-1, regenerative heat exchanger module 4 is more advanced in the cooling mode than regenerative heat exchanger module 5.

When regenerative heat exchanger module 1 has reached the end of its heating mode period, regenerative heat exchanger system controller 100p instructs regenerative heat exchanger module controller 1p to close dampers 1.3.2 and 1.6.2 of regenerative heat exchanger module 1. Simultaneously, regenerative heat exchanger system controller 100p also instructs regenerative heat exchanger module controller 3p to open dampers 3.3.2 and 3.6.2 of previously idle regenerative heat exchanger module 3. During the opening and closing of the dampers, regenerative heat exchanger modules 1 and 3 are in a transition mode (represented by "T" in Table-1).

It is not necessary that the regenerative heat exchanger system controller 100p and the regenerative heat exchanger module controllers 1p, 2p, 3p, 4p, and 5p be located in separate physical instruments. For example, a single programmable logic controller could be used as the regenerative heat exchanger system controller and the regenerative heat exchanger module controllers wherein the functions of the various controllers are located in different parts of a software program. Thus, the regenerative heat exchanger system controller 100p could be written as a parent program, which invokes child programs or sub-programs or sub-routines that in turn function as regenerative heat exchanger module controllers 1p, 2p, 3p, 4p, and 5p.

The stroke times of the actuators in the regenerative heat exchanger modules are adjusted so the time required to open the dampers is equal to the time required to close the dampers. Thus, in Table-1, when dampers 1.3.2 and

1.6.2 are fully closed, dampers 3.3.2 and 3.6.2 are fully opened. Therefore, there is no flow of gas through regenerative heat exchanger module 1, which now becomes an idle regenerative heat exchanger module. The hot gas now flows through regenerative heat exchanger module 3, which is now in the heating mode.

After the idle period has elapsed, regenerative heat exchanger controller 100p conducts a similar sequence of operations to convert regenerative heat exchanger module 4 from a cooling mode to an idle mode and regenerative heat exchanger module 1 from an idle mode to a cooling mode. As described above, regenerative heat exchanger system controller 100p instructs regenerative heat exchanger module controllers 4p and 1p to close dampers 4.4.2 and 4.5.2 in regenerative heat exchanger module 4 and open dampers 1.4.2 and 1.5.2 in regenerative heat exchanger module 1.

The above sequences of operations are carried out for all the regenerative heat exchanger modules so that each regenerative heat exchanger module experiences an idle mode, a heating mode, an idle mode, and a cooling mode. This operation is similar to the operation of a rotary regenerative heat exchanger. The regenerative heat exchanger system of the present invention therefore simulates the operation of the rotary regenerative heat exchanger without the above-described inherent disadvantages of the rotary regenerative heat exchanger.

While Table-1 shows the damper sequence for a regenerative heat exchanger system having an odd number, greater than or equal to, three of regenerative heat exchanger modules, a similar damper sequence can also be developed for a regenerative heat exchanger system having an even number, greater than or equal to two, of regenerative heat exchanger modules. However, in such regenerative heat exchanger systems, there is no pre-set idle mode of operation. As an example, Table-2 shows the damper sequence for a regenerative heat exchanger system having four regenerative heat exchanger modules.

TABLE-2

Regenerative heat exchanger Module No:	1	2	3	4	
Operating Mode:	H	H	C	C	
	T	H	T	C	
	C	H	H	C	
	C	T	H	T	
	C	C	H	H	
	T	C	T	H	
	H	C	C	H	
	H	T	C	T	
	H	H	C	C	(Original condition at start of table)

Yet other operating schemes can be devised according to the control philosophy described above. For example, the five regenerative heat exchanger modules shown in Figure-2 can be operated according to the damper control sequence of Table-1 to provide the maximum thermal efficiency with the minimum pressure fluctuation or cross-leakage of the hot and cold gas streams. In the event of a disabling problem with one of the regenerative heat exchanger modules, the other four regenerative heat exchanger modules can be temporarily operated according to the damper control sequence of Table-2 because each of the regenerative heat exchanger modules is independently operable. This procedure will maintain the operating thermal efficiency with a temporary increase in cross-leakage and pressure fluctuations. This is a major advantage over the rotary regenerative heat exchanger, which has to be totally shut down in case of a problem within any of its heat-transfer sectors.

Similarly, individual regenerative heat exchanger modules can be taken off-line during the night or at other times when reduced electrical demand on the power plant requires that the boiler be operated at reduced capacity. This is a major advantage over the rotary regenerative heat exchanger of the present art wherein such operation generally results in reduced flows and velocities of the hot and cold gases through the rotary regenerative heat exchanger system. Under such operating conditions, the deposition of flyash on the heat sink material surfaces of the rotary regenerative heat exchanger is greatly increased requiring more frequent soot-blowing and increasing the operating cost of the rotary regenerative heat exchanger.

In contrast to the rotary regenerative heat exchanger, the modular regenerative heat exchanger system of the present invention can be designed and operated with varying numbers of regenerative heat exchanger modules to maintain a high design velocity even when the gas flowrate is reduced.

For example, a regenerative heat exchanger system can be designed and operated with seven regenerative heat exchanger modules to accommodate 100 percent of the flowrate of the flue-gas, which is generated by the boiler during the daytime. At nighttime, when the boiler is operated at reduced capacity due to reduced electrical demand on the power plant, the regenerative heat exchanger system can be operated with five or three regenerative heat exchanger modules, as required to accommodate the reduced flowrate of the flue-gas. Operation of the reduced number of regenerative heat exchanger modules at the design flowrate maintains high gas velocities within the heat sink material. The high gas velocities in turn minimize the potential for particulate matter such as flyash in the flue gas stream to deposit within and plug up the flow passages in the heat sink material. Less frequent cleaning of the heat sink material surfaces is required which results in reduced steam or compressed air consumption for soot-blowing, reduced wear and tear of the heat sink material due to the operation of the soot-blower, and reduced operating and maintenance costs.

The number of regenerative heat exchanger modules can be manually or automatically controlled in response to the operating capacity of the boiler. As shown in Figure 3, a boiler capacity sensing means 100s can be used to provide a signal to regenerative heat exchanger system controller 100p to modulate the number of regenerative heat exchanger modules in operation in accordance with the control flow-logic shown in Figure 4. Boiler capacity sensing means 100s can measure an operating variable such as coal fuel or liquid fuel or natural gas fuel firing rate or combustion air flowrate or flue-gas flowrate or boiler feed water flowrate or megawatt-load demand of the electrical grid system or any other operating parameter which can be correlated to the boiler operating level. Such systems are well known in the boiler industry.

Boiler capacity sensing means 100s then provides a signal to the regenerative heat exchanger system controller 100p to indicate the boiler operating level. Regenerative heat exchanger system controller 100p then determines the number of regenerative heat exchanger modules required for optimum operation based upon pre-programmed algorithms which correlate the number of modules to the boiler operating level. Thus, regenerative heat exchanger system controller 100p automatically modulates the number of operating regenerative heat exchanger modules to provide optimum flow velocities in the heat sink material to maximize heat transfer efficiency and reduce flyash deposition.

Another advantage of the system is that selected individual regenerative heat exchanger modules can be isolated from the system for maintenance as required while the boiler is in operation without shutting down the boiler or the entire regenerative heat exchanger system. Because a large number of regenerative heat exchanger modules are used, the removal of individual modules from operation does not greatly reduce the boiler operating capacity.

For example, in an eleven-module regenerative heat exchanger system, one module can be removed from service thereby reducing operating capacity of the boiler by about 20 percent only of the maximum capacity. In comparison, two rotary regenerative heat exchangers are generally used in a conventional boiler system. Therefore, the conventional boiler system capacity is reduced by about 50 percent when one of the rotary regenerative heat exchangers is isolated for repairs or service. Thus a boiler equipped with the modular regenerative heat exchanger system as described herein will provide a higher average annual operating capacity compared to a conventional boiler which is equipped with rotary regenerative heat exchangers.

The regenerative heat exchanger system described above can also be operated with unequal flows or unequal heating and cooling periods or both. As shown as an example in Table 3 in Figure 6, an eight module regenerative heat exchanger system could be operated so that, at any time, four of the eight modules are receiving the hot gas, three modules are receiving the cold gas, and the remaining module is idle. As can be seen, the regenerative heat exchanger modules can be operated such that the heating period is larger than the cooling period.

Alternatively, as shown in Table 4 of Figure 6, the eight module regenerative heat exchanger can be operated so that, at any time, three of the eight modules are receiving the hot gas, three modules are receiving the cold gas, and the remaining two modules are idle. In this case, the regenerative heat exchanger modules can be operated such that the heating period is equal to the cooling period.

As shown in Tables 5, 6, 7, and 8 of Figure 6, any combination of heating, cooling, and idle modules can be chosen to simulate the operation of a rotary regenerative heat exchanger with a variable number of heat transfer sectors. Also, the heating and cooling periods can be kept the same as in the original operation or they can be changed to keep the original total cycle time. Thus, as an example in Table 5, one regenerative heat exchanger module is taken off-line (as indicated by "O"), three regenerative heat exchanger modules are heating, three regenerative heat exchanger modules are cooling, and one regenerative heat exchanger module is idle. As a further example, in Table 6, four regenerative heat exchanger modules are heating, three regenerative heat exchanger modules are cooling, and one regenerative heat exchanger module is off-line. In Tables 5 and 6, the new cycle time, with the reduced number of regenerative heat exchanger modules in operation, can be shortened to 70 seconds by maintaining the original switch time of 10 seconds. Alternately, the cycle time can be maintained at 80 seconds, even with the reduced number of regenerative heat exchanger modules in operation, by increasing the switch time to 8/7*10 or 11.43 seconds.

As yet another example, in Table 7, three regenerative heat exchanger modules are heating, three regenerative heat exchanger modules are cooling, and two regenerative heat exchanger modules are off-line. As a final example, in Table 8, two regenerative heat exchanger modules are heating, three regenerative heat exchanger modules are cooling, and three regenerative heat exchanger modules are off-line. In Tables 7 and 8, the new cycle time, with the reduced number of regenerative heat exchanger modules in operation, can be shortened to 60 seconds by maintaining the original switch time of 10 seconds. Alternately, the cycle time can be maintained at 80 seconds, even with the reduced number of regenerative heat exchanger modules in operation, by increasing the switch time to 8/6*10 or 13.33 seconds. As a general case, the regenerative heat exchanger module system can be maintained at the original cycle time by increasing the switch time to (N/(N-O))*S where N equals the total number of originally operating modules, O equals the number of off-line modules, and S equals the original switch time.

From the above examples, it will be obvious, that any combinations of heating, cooling, idle, and off-line regenerative heat exchanger modules can be operated at any time. This feature is especially usefully, for conducting preventative maintenance or repairs to selected regenerative heat exchanger modules without shutting down the boiler or the regenerative heat exchanger system. Further, this feature is also useful for operating the regenerative heat exchanger system under low-load conditions as dictated by power grid demands on the powerplant. This feature of operating a variable number of regenerative heat exchanger modules provides great operating advantages over rotary regenerative heat exchanger systems in which the number of regenerative heat exchanger sectors is fixed at design. The invention allows a varying number of regenerative heat exchanger modules to be automatically put on-line or taken off-line in response to boiler operating level without affecting the overall operation of the boiler or the regenerative heat exchanger system.

Yet other advantages of the modular regenerative heat exchanger system described herein will be obvious to persons skilled in the art. It should be understood, of course, that the foregoing relates to preferred embodiments of the invention and that modifications may be made without departing from the spirit and scope of the invention as set forth in the following claims.